On the Solar Neutrino Problems, SNO experimental data and low–energy nuclear forces

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Abstract

The Solar Neutrino Problems (SNP's) are analysed within the Standard Solar Model (BP2000) supplemented by the reduction of the solar neutrino fluxes through the decrease of the solar core temperature. The former can be realized through the enhancement of the astrophysical factor for solar proton burning. The enhancement, the upper bound of which is restricted by the helioseismological data, goes dynamically due to low–energy nuclear forces described at the quantum field theoretic level. The agreement of the reduced solar neutrino fluxes with the experimental data is obtained within the scenario of vacuum two–flavour neutrino oscillations. We show that by fitting the mean value of the solar neutrino flux measured by HOMESTAKE Collaboration we predict the high energy solar neutrino flux measured by SNO Collaboration $\Phi^{\rm SNO}_{\rm th}(^8{\rm B}) = 1.73\times 10^6\,{\rm cm^{-2}\,s^{-1}}$ in perfect agreement with experimental value $\Phi^{\rm SNO}_{\rm exp}(^8{\rm B}) = (1.75\pm 0.14)\times 10^6\,{\rm cm^{-2}\,s^{-1}}$ obtained via the measurement of the rate of reaction $\nu_{\rm e} + {\rm D} \to {\rm p} + {\rm p} + {\rm e}^-$ produced by ^{8}B solar neutrinos. The theoretical flux for low–energy neutrino flux measured by GALLIUM (GALLEX, GNO and SAGE) Collaborations $S^{\rm Ga}_{\rm th} = 65\,{\rm SNU}$ agrees with the experimental data averaged over experiments $S^{\rm Ga}_{\rm exp} = (75.6\pm 4.8)\,{\rm SNU}$.

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1 Solar neutrino fluxes. Theory and Experiment

The Solar Neutrino Problem (SNP) [1,2] as the disagreement with the theoretical prediction and the seminal experimental data by Raymond Davis [3] has been recently reformulated by Bahcall in the form of Three Solar Neutrino Problems [4]. The solution of these SNP's demands simultaneous description of the experimental data by HOMESTAKE, GALLEX–GNO–SAGE, SUPERKAMIOKANDE and SNO Collaborations [4].

Nowadays there is no doubts that the solution of the SNP's goes via the application of a mechanism of neutrino oscillations introduced in physics by Gribov and Pontecorvo [5,6]. According to Gribov–Pontecorvo's hypothesis electronic neutrinos $\nu_{\rm e}$ produced in the solar core can change their flavour due to the transition $\nu_{\rm e} \to \nu_{\mu}$ during their travel to the Earth. The former should obviously diminish the flux of solar electronic neutrinos measured on the Earth.

The solar core can interfere in the process of neutrino oscillations in a twofold way. First, neutrino oscillations can be resonantly enhanced by virtue of the solar core matter suggested by Wolfenstein, Mikheyev and Smirnov [7], so–called the MSW effect [8], and, secondary, due to low–energy nuclear forces contributing to nuclear reaction on $\nu_{\rm e}$–neutrino production. The most popular is the MSW effect, since it allows to diminish the solar neutrino fluxes without change of the main parameters of the Standard Solar Model (SSM BP2000) formulated by Bahcall with co–workers [9,10].

The main nuclear reaction in the Sun is the solar proton burning $\rm p + p \to D + e^+ + \nu_e$. It is induced by the charge weak current, that is defined by the W^+–boson exchange, and strong low–energy nuclear forces. The reaction $\rm p + p \to D + e^+ + \nu_e$ gives start the p–p chain of nucleosynthesis in the Sun and main–sequence stars [2,11]. In the SSM the total (or bolometric) luminosity of the Sun $L_{\odot} = (3.846 \pm 0.008) \times 10^{26}\,{\rm W}$ is normalized to the astrophysical factor $S_{\rm pp}(0)$ for the solar proton burning. The recommended value $S^{\rm SSM}_{\rm pp}(0) = 4.00 \times 10^{-25}\,{\rm MeVb}$ [12]. The helioseismological data restrict the value of the astrophysical factor $S_{\rm pp}(0)$ and predict $0.94 \le S_{\rm pp}(0)/S^{\rm SSM}_{\rm pp}(0) \le 1.18$ [13].

The interference of low–energy nuclear forces into neutrino production can be realized in the form of an enhancement of the astrophysical factor $S_{\rm pp}(0)$. As has been recently shown within both the Nambu–Jona–Lasinio model of light nuclei (the NNJL model) [14-16] and the Effective Field Theory (EFT) [17–19] the astrophysical factor $S_{\rm pp}(0)$ calculated within quantum field theoretic models contains an arbitrary parameter which can be fixed from the experimental data on the reactions for disintegration of the deuteron by neutrinos and antineutrinos [16–19]. For example, in the NNJL model the astrophysical factor $S_{\rm pp}(0)$ is defined by [15,16]

$$S_{\rm pp}(0) = (1 + \bar{\xi}\,)^2 \times 4.08 \times 10^{-25}\,{\rm MeV\,b}, \tag{1.1}$$

where $\bar{\xi}$ is an arbitrary parameter (see Appendix of Ref. [15]) and Ref. [16]. The same factor appears in the cross sections for neutrino and antineutrino disintegration of the deuteron [15,16]. For example, for the cross sections for the disintegration of the deuteron by reactor antineutrinos averaged over the antineutrino energy spectrum we have [15]

$$\begin{aligned}\langle\sigma^{\bar{\nu}_{\rm e}{\rm D}\to {\rm e}^+{\rm nn}}(E_{\bar{\nu}_{\rm e}})\rangle &= (1+\bar{\xi})^2 \times 11.56 \times 10^{-45}\,{\rm cm}^2,\\ \langle\sigma^{\bar{\nu}_{\rm e}{\rm D}\to \bar{\nu}_{\rm e}{\rm np}}(E_{\bar{\nu}_{\rm e}})\rangle &= (1+\bar{\xi})^2 \times 6.28 \times 10^{-45}\,{\rm cm}^2,\end{aligned} \tag{1.2}$$

The experimental values of these cross sections read [20]

$$\begin{aligned}\langle\sigma^{\bar{\nu}_{\rm e}{\rm D}\to{\rm e}^+{\rm nn}}(E_{\bar{\nu}_{\rm e}})\rangle_{\rm exp} &= (9.83\pm 2.04)\times 10^{-45}\,{\rm cm}^2,\\ \langle\sigma^{\bar{\nu}_{\rm e}{\rm D}\to\bar{\nu}_{\rm e}{\rm np}}(E_{\bar{\nu}_{\rm e}})\rangle_{\rm exp} &= (6.08\pm 0.77)\times 10^{-45}\,{\rm cm}^2.\end{aligned}\tag{1.3}$$

We would like to accentuate that the averaged value of the cross section for the reaction $\bar{\nu}_{\rm e} + {\rm D} \to {\rm n} + {\rm n} + {\rm e}^+$ has been calculated without account for reactor antineutrino oscillations [21–23] which should diminish the theoretical values of the cross section [22].

In Ref. [16] there has been a suggestion to use the ambiguity in the calculation of the astrophysical factor in order to enhance its value. This should lead to the decrease of the solar core temperature. Indeed, any change of the astrophysical factor $S_{\rm pp}(0)$ entails the change of the solar core temperature [24]:

$$\frac{\Delta T_c}{T^{\rm SSM}_c} = -\,0.15\,\frac{\Delta S_{\rm pp}(0)}{S^{\rm SSM}_{\rm pp}(0)}.\tag{1.4}$$

The enhancement of the astrophysical factor relative to the standard value $S^{\rm SSM}_{\rm pp}(0) = 4.00\times 10^{-25}\,{\rm MeV\,b}$, i.e. $\Delta S_{\rm pp}(0) > 0$, provides the decrease of the solar core temperature. The maximal decrease of T_c is restricted from above by the inequality $\Delta S_{\rm pp}(0) \le 0.18\,S^{\rm SSM}_{\rm pp}(0)$ that has been pointed out by Degl'Innocenti, Fiorentini and Ricci [13]. Hence, the minimal value of the solar core temperature, calculated for $T^{\rm SSM}_c = 1.57\times 10^7\,{\rm K}$ [10], can be equal to

$$T_c = 1.53\times 10^7\,{\rm K}.\tag{1.5}$$

It is well–known that solar neutrino fluxes are sensitive to the value of the solar core temperature [25]. By using a temperature dependence of the solar neutrino fluxes obtained by Bahcall and Ulmer [25]: $\Phi({\rm pp}) \propto T^{-1.1}_c$, $\Phi({\rm pep}) \propto T^{-2.4}_c$, $\Phi({}^7{\rm Be}) \propto T^{10}_c$, $\Phi({}^8{\rm B}) \propto T^{24}_c$, $\Phi({}^{13}{\rm N}) \propto T^{24.4}_c$ and $\Phi({}^{15}{\rm O}) \propto T^{27.1}_c$ we can calculate the solar neutrino fluxes for the reduced solar core temperature Eq.(1.5). The new values of the solar neutrino fluxes are given in Table 3.

It is seen that the solar neutrino fluxes calculated for the solar core temperature $T_c = 1.53\times 10^7\,{\rm K}$ are still not enough decreased in order to satisfy the experimental data. Therefore, for the reduction of the solar neutrino fluxes, taking place outside the solar core, we will use the mechanism of neutrino oscillations. We will follow the simplest scenario of vacuum two–flavour neutrino oscillations suggested by Gribov and Pontecorvo [5,6]. By virtue of the vacuum two–flavour neutrino oscillations $\nu_{\rm e} \to \nu_\mu$ the solar neutrino fluxes should be multiplied by the factor [5]

$$P_{\nu_{\rm e}\to\nu_{\rm e}}(E_{\nu_{\rm e}}) = 1 - \frac{1}{2}\,\sin^2 2\,\theta\,\Big(1 - \cos\frac{\Delta m^2 L}{2E_{\nu_{\rm e}}}\Big),\tag{1.6}$$

where $\Delta m^2 = m^2_{\nu_\mu} - m^2_{\nu_{\rm e}}$, L is the distance of the neutrino's travel, $E_{\nu_{\rm e}}$ is a neutrino energy and θ is a neutrino–flavour mixing angle [5]. After the averaging over energies and for L of order of the Sun–Earth distance the solar neutrino fluxes become multiplied by a factor [6]

$$\overline{P_{\nu_{\rm e}\to\nu_{\rm e}}(E_{\nu_{\rm e}})} = 1 - \frac{1}{2}\,\sin^2 2\,\theta.\tag{1.7}$$

The result of the integration over energies Eq.(1.6) can occur only if $\Delta m^2 L/2E_{\nu_{\rm e}}$ obeys the constraint

$$\frac{\Delta m^2 L}{2E_{\nu_{\rm e}}} \gg 1. \tag{1.8}$$

If we would like to get the factor Eq.(1.7) for all solar neutrino fluxes including the ^{8}B neutrinos, so that the upper bound on the neutrino energies should coincide with the upper bound on the ^{8}B neutrino energy spectrum and should be equal to $E_{\nu_{\rm e}} = 15\,{\rm MeV}$. As the Sun–Earth distance L amounts to $L = 1.496 \times 10^{13}\,{\rm cm} = 7.581 \times 10^{23}\,{\rm MeV}^{-1}$, the inequality Eq.(1.7) gives the lower bound on Δm^2:

$$\Delta m^2 \gg 4 \times 10^{-11}\,{\rm eV}^2. \tag{1.9}$$

The value of the mixing angle $\sin^2 2\theta$ we can get fitting, for example, the mean value of the neutrino flux measured by HOMESTAKE Collaboration. This gives

$$\sin^2 2\theta = 0.838. \tag{1.10}$$

The solar neutrino fluxes reduced by virtue of vacuum two–flavour neutrino oscillations are adduced in Table 4. One can see a reasonable agreement between theoretical and experimental values of the solar neutrino fluxes for GALLEX–GNO and SAGE experiments.

The relation of the solar neutrino flux $\Phi_{\rm exp}(^8{\rm B})$ measured by SUPERKAMIOKANDE and SNO Collaborations to the solar ^{8}B neutrino flux $\Phi(^8{\rm B})$ can be derived by following Bahcall *et al.* [26]. With accuracy better than 2% the theoretical expression for the solar neutrino flux $\Phi^{\rm SNO}_{\rm th}(^8{\rm B})$ is given by

$$\Phi^{\rm SNO}_{\rm th}(^8{\rm B}) = \left(1 - \frac{4\,\sin^2 2\theta\,\sin^2\theta_{\rm W}}{(1\,+\,2\,\sin^2\theta_{\rm W})^2}\right)\Phi(^8{\rm B}) = (1.73^{+0.34}_{-0.24}) \times 10^6\,{\rm cm^{-2}s^{-1}}, \tag{1.11}$$

where $\theta_{\rm W}$ is the Weinberg's mixing angle of the Standard electroweak model defined by $\sin^2\theta_{\rm W} = 0.225$ [27]. The theoretical value $\Phi^{\rm SNO}_{\rm th}(^8{\rm B}) = (1.73^{+0.34}_{-0.24}) \times 10^6\,{\rm cm^{-2}s^{-1}}$ is in excellent agreement with recent experimental data by SNO Collaboration $\Phi^{\rm SNO}_{\rm exp}(^8{\rm B}) = (1.75 \pm 0.14) \times 10^6\,{\rm cm^{-2}s^{-1}}$ measured from the rate of the reaction $\nu_{\rm e} + {\rm D} \to {\rm p} + {\rm p} + {\rm e}^-$ produced by ^{8}B solar neutrinos (see Table 1).

The general expressions for the solar neutrino fluxes as functions of the solar neutrino flux $\Phi_{\rm exp}(^8{\rm B})$ measured by SNO and SUPERKAMIOKANDE Collaborations and the mixing angle θ can be obtained as follows [16]. From Eq.(1.9) we express $\Phi(^8{\rm B})$ in terms of the solar neutrino flux $\Phi_{\rm exp}(^8{\rm B})$ and the mixing angle. Setting $\sin^2\theta_{\rm W} = 0.225$ and denoting $\Phi_{\rm exp}(^8{\rm B}) = \lambda \times 10^6\,{\rm cm^{-2}s^{-1}}$ we get

$$\Phi(^8{\rm B}) = \lambda \times 10^6\,(1 - 0.428\,\sin^2 2\theta)^{-1}\,{\rm cm^{-2}s^{-1}}. \tag{1.12}$$

The ratio of the solar core temperatures $T_c/T^{\rm SSM}_c$ is then defined by

$$\frac{T_c}{T^{\rm SSM}_c} = 0.934\,\lambda^{1/24}(1 - 0.428\,\sin^2 2\theta)^{-1/24}. \tag{1.13}$$

The solar neutrino fluxes as functions of $\sin^2 2\theta$ and λ measured in $10^{10}\,\mathrm{cm^{-2}s^{-1}}$ read [16]:

$$\begin{aligned}
\Phi(\mathrm{pp}) &= 6.403\,\lambda^{-1.1/24}(1-0.428\,\sin^2 2\theta)^{1.1/24},\\
\Phi(\mathrm{pep}) &= 1.638\times 10^{-2}\,\lambda^{-1/10}(1-0.428\,\sin^2 2\theta)^{1/10},\\
\Phi({}^7\mathrm{Be}) &= 2.425\times 10^{-1}\,\lambda^{10/24}(1-0.428\,\sin^2 2\theta)^{-10/24},\\
\Phi({}^8\mathrm{B}) &= 1.000\times 10^{-4}\,\lambda\,(1-0.428\,\sin^2 2\theta)^{-1},\\
\Phi({}^{13}\mathrm{N}) &= 1.144\times 10^{-2}\,\lambda^{24.4/24}(1-0.428\,\sin^2 2\theta)^{-24.4/24},\\
\Phi({}^{15}\mathrm{O}) &= 0.836\times 10^{-2}\,\lambda^{27.1/24}(1-0.428\,\sin^2 2\theta)^{-27.1/24}.
\end{aligned}\tag{1.14}$$

The theoretical expressions for the solar neutrino fluxes measured by HOMESTAKE, GALLEX–GNO and SAGE experiments are given by

$$\begin{aligned}
&S^{\mathrm{Cl}}_{\mathrm{th}} = (1-0.5\,\sin^2 2\theta)\\
&\times[0.236\,\lambda^{-1/10}(1-0.428\,\sin^2 2\theta)^{1/10}+0.582\,\lambda^{10/24}(1-0.428\,\sin^2 2\theta)^{-10/24}\\
&+0.019\,\lambda^{24.4/24}(1-0.428\,\sin^2 2\theta)^{-24.4/24}+0.063\,\lambda^{27.1/24}(1-0.428\,\sin^2 2\theta)^{-27.1/24}\\
&+1.146\,\lambda\,(1-0.428\,\sin^2 2\theta)^{-1}],\\
&S^{\mathrm{Ga}}_{\mathrm{th}} = (1-0.5\,\sin^2 2\theta)\\
&\times[75.043\,\lambda^{-1.1/24}(1-0.428\,\sin^2 2\theta)^{1.1/24}+3.300\,\lambda^{-1/10}(1-0.428\,\sin^2 2\theta)^{1/10}\\
&+17.380\,\lambda^{10/24}(1-0.428\,\sin^2 2\theta)^{-10/24}+0.700\,\lambda^{24.4/24}(1-0.428\,\sin^2 2\theta)^{-24.4/24}\\
&+0.943\,\lambda^{27.1/24}(1-0.428\,\sin^2 2\theta)^{-27.1/24}+2.408\,\lambda\,(1-0.428\,\sin^2 2\theta)^{-1}],
\end{aligned}\tag{1.15}$$

where the factor $(1-0.5\,\sin^2 2\theta)$ takes into account the contribution of vacuum two–flavour neutrino oscillations.

2 Conclusion

We have suggested a reduction of the solar core temperature due to a dynamics of low–energy nuclear forces described at the quantum field theoretic level [14–19]. We have shown that the reduction of the solar neutrino fluxes in the solar core caused by the decrease of the solar core temperature supplemented by the scenario of vacuum two–flavour neutrino oscillations $\nu_{\mathrm{e}} \leftrightarrow \nu_{\mu}$ during the travel of solar neutrinos to the Earth proposed by Gribov and Pontecorvo [5] gives a reasonable theoretical basis for the understanding of the SNP's formulated by Bahcall [4].

It is important to emphasize that the necessary reduction of the solar core temperature makes up only 2.7% of the temperature recommended by SSM (BP2000) [10]

$$\Delta(T_c) = \frac{T^{\mathrm{SSM}}_c - T_c}{T^{\mathrm{SSM}}_c} = 2.7\,\%.$$

This agrees with the constraints $\Delta(T_c) = \pm 6\%$ on the solar core temperature fluctuations given by Bethe and Bahcall [34].

Due to the reduction of the neutrino fluxes in the solar core for the secondary reduction caused by two–flavour neutrino oscillations we obtain $\Delta m^2 \gg 4\times 10^{-11}\,\mathrm{eV}^2$ and $\sin^2 2\theta = 0.838$. This allows a simultaneous description of the experimental data on the solar neutrino fluxes with an accuracy not worse than the theoretical accuracy of the SSM (BP2000). The constraint $\Delta m^2 \gg 4\times 10^{-11}\,\mathrm{eV}^2$ is rather general and makes the analysis of two–flavour neutrino oscillations much more flexible with respect to different experimental data on parameters of neutrino–flavour oscillations [35].

The mixing angle $\sin^2 2\theta = 0.838$ has been obtained by fitting the *mean value* of the experimental flux measured by HOMESTAKE. The theoretical value of the low–energy solar neutrino flux $S^{\rm Ga}_{\rm th} = 65\,{\rm SNU}$ agrees with experimental data by GALLIUM Collaborations $S^{\rm Ga}_{\rm exp} = (75.6 \pm 4.8)\,{\rm SNU}$ averaged over experiments. Our theoretical prediction for the ${}^8{\rm B}$ solar neutrino flux $\Phi^{\rm exp}_{\rm TH}({}^8{\rm B}) = 1.73 \times 10^6\,{\rm cm^{-2}\,s^{-1}}$, that should be measured on the Earth, is in perfect agreement with the experimental value $\Phi^{\rm exp}_{\rm SNO}({}^8{\rm B}) = (1.75 \pm 0.14) \times 10^6\,{\rm cm^{-2}\,s^{-1}}$ obtained via the measurement of the rate of reaction $\nu_{\rm e} + {\rm D} \to + {\rm p} + {\rm p} + {\rm e}^-$ produced by ${}^8{\rm B}$ solar neutrinos. The cross section for the reaction $\nu_{\rm e} + {\rm D} \to + {\rm p} + {\rm p} + {\rm e}^-$ as well as the astrophysical factor for the solar proton burning $S_{\rm pp}(0)$ is induced by the weak charge current and defined by low–energy nuclear forces, which are described well by the NNJL model in complete agreement with nuclear phenomenology. For example, the D–wave component of the wave function of the deuteron $D/S = 0.0238$, calculated relative to the S–wave component without input parameters (see EPJA**12**, 87 (2001) of Ref.[14]), is in agreement with the phenomenological value $D/S = 0.0256 \pm 0.0004$ used by Kamionkowski and Bahcall for the description of the realistic wave function of the deuteron in connection with the calculation of the astrophysical factor $S_{\rm pp}(0)$ within the potential model approach [36]. The reaction $\nu_{\rm e} + {\rm D} \to + {\rm p} + {\rm p} + {\rm e}^-$ is very sensitive to neutrino oscillations and reproduces the net rest of the solar neutrino flux originated by the boron decay ${}^8{\rm B} \to {}^8{\rm Be}^* + {\rm e}^+ + \nu_{\rm e}$ in the solar core. Since the cross section for the reaction $\nu_{\rm e} + {\rm D} \to + {\rm p} + {\rm p} + {\rm e}^-$ is defined in the NNJL model by the same dynamics of strong low–energy nuclear forces as the astrophysical factor $S_{\rm pp}(0)$, the obtained agreement becomes not surprising. Such an agreement testifies also the consistency of the dynamics of strong low–energy nuclear forces described by the NNJL model as well as the EFT with the SSM (BP2000) [10]. In fact, the neutrino fluxes decreased by the change of the solar core temperature are fully determined by the SSM (BP2000) and the temperature law–scaling suggested by the SSM [25].

Thus, the suggested scenario of the evolution of solar neutrino fluxes reconciles the experimental data on high energy solar neutrino fluxes by HOMESTAKE, SNO and SUPERKAMIOKANDE Collaborations and low–energy solar neutrino fluxes by GALLIUM Collaborations GALLEX, GNO and SAGE with theoretical predictions and relaxes the stress of the SNP's formulated by Bahcall [4].

Since the constraint $\Delta m^2 \gg 4\times 10^{-11}\,\mathrm{eV}^2$ means that effectively the theoretical values of the solar neutrino fluxes do not depend on Δm^2, the agreement between theoretical solar neutrino fluxes and experimental data is reached by virtue of the tuning of only two parameters (i) the solar core temperature T_c, diminished by 2.7% relative to the solar core temperature recommended by SSM (BP2000) due to the dynamics of low–energy nuclear forces and restricted from above by helioseismological data, and (ii) the mixing angle $\sin^2\theta = 0.838$, fixed by the fit of the mean value of the solar neutrino flux measured by HOMESTAKE Collaboration.

The theoretical predictions for two–flavour neutrino–oscillation parameters: $\Delta m^2 \gg 4 \times 10^{-11}\,\mathrm{eV}^2$ and $\sin^2 2\theta = 0.838$ should be applied to the calculation of the contribution of reactor antineutrino oscillations [21–23] to the cross sections for antineutrino disintegration of the deuteron $\bar{\nu}_{\rm e}$ + D $\to$ n + n + $\rm e^+$ and $\bar{\nu}_{\rm e}$ + D $\to$ n + p + $\bar{\nu}_{\rm e}$ in order rearrange the theoretical enhancement of the astrophysical factor $S_{\rm pp}(0)$ with theoretical cross sections for the reactions $\bar{\nu}_{\rm e}$ + D $\to$ n + n + $\rm e^+$ and $\bar{\nu}_{\rm e}$ + D $\to$ n + p + $\bar{\nu}_{\rm e}$ and experimental data of Reines's experimental group [20]. We are planning to carry out this work in our forthcoming publications.

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Table 1. Solar neutrino data, $1\,\mathrm{SNU} = 10^{-36}\,\mathrm{events/(atoms\cdot s)}$. The error is defined as $\sigma = \sqrt{(\mathrm{stat.})^2 + (\mathrm{syst.})^2}$

Experiment	Data $\pm\sigma$	Units
HOMESTAKE [28] $\nu_\mathrm{e} + {}^{37}\mathrm{Cl} \to \mathrm{e}^- + {}^{37}\mathrm{Ar}$ $E_\mathrm{th} = 0.81\,\mathrm{MeV}$	2.56 ± 0.23	SNU
SAGE [29] $\nu_\mathrm{e} + {}^{71}\mathrm{Ga} \to \mathrm{e}^- + {}^{71}\mathrm{Ge}$ $E_\mathrm{th} = 0.23\,\mathrm{MeV}$	77.0 ± 6.7	SNU
GALLEX + GNO [30] $\nu_\mathrm{e} + {}^{71}\mathrm{Ga} \to \mathrm{e}^- + {}^{71}\mathrm{Ge}$ $E_\mathrm{th} = 0.23\,\mathrm{MeV}$	74.1 ± 6.8	SNU
KAMIOKANDE [31] $\nu_\mathrm{e} + \mathrm{e}^- \to \mathrm{e}^- + \nu_\mathrm{e}$ $E_\mathrm{th} = 7.0\,\mathrm{MeV}$	2.80 ± 0.38	$10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
SUPERKAMIOKANDE [32] $\nu + \mathrm{e}^- \to \nu + \mathrm{e}^-$ $E_\mathrm{th} = 5.5\,\mathrm{MeV}$	2.32 ± 0.09	$10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
SNO [33] $\nu + \mathrm{D} \to \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ $E_\mathrm{th} = 7.26\,\mathrm{MeV}$	1.75 ± 0.14	$10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
SNO [33] $\nu + \mathrm{e}^- \to \nu + \mathrm{e}^-$ $E_\mathrm{th} = 7.26\,\mathrm{MeV}$	2.39 ± 0.34	$10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Table 2. Standard Solar Model (BP2000) predictions for the solar neutrino fluxes normalized to the recommended value of the astrophysical factor $S_\mathrm{pp}(0) = 4.00 \times 10^{-25}\,\mathrm{MeV\,b}$ (see Table 7 of Ref. [10]).

Source	Flux ($10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Cl (SNU)	Ga (SNU)	SNO – SK ($10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
pp	$5.95(1.00 \pm 0.01)$	0.0	69.7	
pep	$1.40 \times 10^{-2}(1.00 \pm 0.015)$	0.22	2.8	
^{7}Be	$4.77 \times 10^{-1}(1.00 \pm 0.01)$	1.15	34.2	
^{8}B	$5.05 \times 10^{-4}(1.00^{+0.20}_{-0.16})$	5.76	12.1	$5.05(1.00^{+0.20}_{-0.16})$
^{13}N	$5.48 \times 10^{-2}(1.00^{+0.21}_{-0.17})$	0.09	3.4	
^{15}O	$4.80 \times 10^{-2}(1.00^{+0.25}_{-0.19})$	0.33	5.5	
		$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}	$5.05^{+1.01}_{-0.81}$

Table 3. The solar neutrino fluxes normalized to astrophysical factor $S_{\rm pp}(0) = 4.72 \times 10^{-25}\,{\rm MeV\,b}$ caused by the non–trivial contribution of the nucleon tensor current [15,16].

Source	Flux ($10^{10}\,{\rm cm^{-2}s^{-1}}$)	Cl (SNU)	Ga (SNU)	SNO – SK ($10^{6}\,{\rm cm^{-2}s^{-1}}$)
pp	6.10	0.0	71.49	
pep	1.48×10^{-2}	0.21	2.98	
^{7}Be	3.66×10^{-1}	0.88	26.23	
^{8}B	2.69×10^{-4}	3.08	6.46	2.69
^{13}N	3.13×10^{-2}	0.05	1.91	
^{15}O	2.56×10^{-2}	0.19	2.89	
		4.41	111.96	

Table 4. The solar neutrino fluxes normalized to $S_{\rm pp}(0) = 1.18\,S^{\rm SSM}_{\rm pp}(0) = 4.72 \times 10^{-25}\,{\rm MeV\,b}$. The theoretical values of experimentally measured neutrino fluxes are calculated within a scenario of vacuum two–flavour neutrino oscillations at $\sin^2 2\theta = 0.838$. The error is defined as $\sqrt{({\rm stat.})^2 + ({\rm syst.})^2}$. The experimental value of GALLIUM Collaborations is averaged over experimental data (see Table 1 of Ref. [4], hep–ph/0108147).

Source	Flux ($10^{10}\,{\rm cm^{-2}s^{-1}}$)	Cl (SNU)	Ga (SNU)	SNO – SK ($10^{6}\,{\rm cm^{-2}s^{-1}}$)
pp	6.10	0.0	41.54	
pep	1.48×10^{-2}	0.13	1.73	
^{7}Be	3.66×10^{-1}	0.50	15.25	
^{8}B	2.69×10^{-4}	1.79	3.74	1.73
^{13}N	3.13×10^{-2}	0.03	1.11	
^{15}O	2.56×10^{-2}	0.11	1.68	
		$2.56^{+0.40}_{-0.33}$	$65.05^{+4.03}_{-3.06}$	$1.73^{+0.34}_{-0.24}$
		2.56 ± 0.23	75.6 ± 4.8	1.75 ± 0.14

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